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NEW ENERGETICS

Effect of Torrefaction on Properties of Solid Granulated Fuel of Different Biomass Types[1]

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Abstract—Possibilities of application of low-temperature pyrolysis (torrefaction) for improvement of thermotechnical characteristics of biomass granulated fuel are considered. The data on hygroscopic properties, content of volatile matter and heating value of the torrefied biomass fuel produced under various conditions of processing of such types of biomass as wood, peat, and agricultural waste are presented. It is shown that the high-temperature conversion of gases and vapors, escaping during torrefaction, into synthesis gas is an effective method of their environmentally friendly utilization and, at the same time, increases the energy efficiency of biomass processing to granulated fuel.

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INTRODUCTION

At present biomass is widely used for power generating purposes. It is caused by development of self-sufficient power units, increasing attention to ecological aspects of heat and electric power production, availability and renewable character of biomass as a fuel, tendency to energy safety of regions and countries. There are different methods of power utilization of biomass, namely, direct use as a solid fuel, processing into gaseous or liquid fuel [1]. As a solid fuel, biomass has several disadvantages, in particular, high hygroscopicity, a low bulk density (this is first of all referred to agricultural waste) and as a consequence low volumetric energy density. In spite of distinctions in the properties of wood, agro waste (straw, sunflower and rice husk) and peat, the production of granulated solid fuel (pellets) from mentioned types of biomass has obtained a wide spread occurrence. Pelletization, that is densification of an initial raw material, leads to a noticeable increase in the volumetric energy density of the solid biofuel [2]. As a result, the granulated biofuel is suitable for use in automated heating and power generation systems [3]. At the same time, pelletization practically has no effect on the energy density on a mass basis and aggravates the situation with hydrophobic properties: when in contact with water or being in a humid environment pellets swell and disintegrate into the original particles. This behavior is one of the main demerits of biomass pellets as it complicates storage and transportation and requires the use of a moisture-proof packaging.

Improvement of hydrophobic properties of granulated biomass fuel can be achieved by thermal treatment. The thermal treatment at the temperatures up to 300°C, carried out in the inert gas environment (low-temperature or mild pyrolysis), leads to an improvement of consumer properties of solid biofuel. In scientific literature this process is known as a torrefaction. In course of torrefaction not only the moisture removal from an initial raw material, i.e. its drying, occurs but also partial thermal decomposition of biomass organic constituents takes place [4]. As a result a solid hydrophobic product is formed. In addition its heating value (on a mass basis) Q_t surpasses a similar value for initial raw material Q. When woody biomass is used as initial raw material the value of Q_t can reach 19–23 MJ/kg, depending on conditions at which the torrefaction is carried out [2]. Note that the heating value of a dry wood and wood pellets doesn't exceed 18 MJ/kg.

In principle, torrefaction can be used both a prior operation before pelletization [2, 5], and as processing of the solid granulated (briquetted) fuel from biomass [6]. The question of whether in which sequence it is advisable to carry out the processing of raw biomass into solid fuel—torrefaction, and then densification or vice versa—is debatable. Both approaches have their advantages and disadvantages. In the first case, the end product has higher bulk density and higher heating value on a mass bases [2]. According to [2, 7] the densification of torrefied biomass leads to significantly reduction of the energy consumption for the production of granulated biofuel in comparison with the production of conventional pellets. Since torrefied biomass is more friable substance, the power consumption for its grinding is significantly less than in case of raw biomass [2, 8], and as follows from the data presented in [9] it decreases with increase in torrefac-

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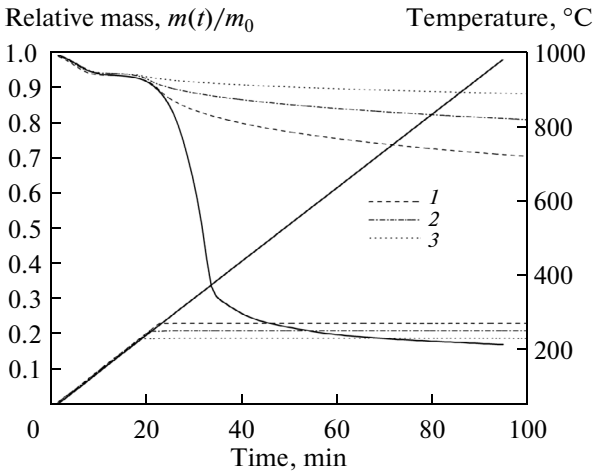

Fig. 1. Mass losses and temperature profiles during pyrolysis and torrefaction of wood pellets at different final temperatures (m_0 and $m(t)$—initial and current mass of the sample): T_t = (*1*) 270, (*2*) 250, and (*3*) 230°C.

tion temperature. However, in [2, 7] data on power consumption characteristics of densification of torrefied biomass are absent. At the same time in [10, 11] there are presented data from which it follows that power consumption for pelletizing of torrefied biomass is essentially higher than for pelletizing of untreated biomass. Attempt to reduce it by addition of water to the milled torrefied biomass does not improve the situation [10]. Furthermore, during pelletization of the torrefied biomass it is necessary to use binding agents [12]. Nevertheless, in the overwhelming majority of publications on torrefaction the properties of pellets, made from torrefied biomass, are considered. Papers, devoted to investigations of influence of heating conditions on properties of pregranulated biomass, are practically absent.

The present paper is devoted to investigation of torrefaction process and effect of the torrefaction conditions on such properties of pregranulated biofuel of different biomass types as devolatilization, heating value and hygroscopicity. Here a comparison of the properties of torrefied pellets made from three types of biomass, namely, straw, wood and peat is presented. One of the problems, that arises during torrefaction, is utilization of the evolved pyrolysis gases and vapors. Its decision is important from ecological point of view. The possibility of thermal conversion of volatile products, escaping during torrefaction of different types of biomass, into synthesis gas is also considered. The experimental data on the quantity and composition of synthesis gas, which can be obtained as a result of biomass torrefaction and subsequent thermal processing of volatile products, are presented.

EXPERIMENTAL CONDITIONS

As raw materials there were used such types of biomass as wood, straw and peat. The choice of these raw materials was determined the fact that wood and straw are the most common waste products of industry and agriculture, peat—organic raw material formed as a result of the partial biodegradation of vegetation—is widespread in nature and is related to renewable hydrocarbon resources. Thermal processing of pellets from the mentioned biomass materials was carried out on a laboratory scale installation and consisted in their heating in the inert gas environment (nitrogen) to the torrefaction temperature T_t = 230, 250 and 270°C at the rate of 10°C/min and holding at this temperature for some time.

When heating biomass there is its thermal decomposition and as a result a residual char and volatile products are formed [13]. The volatile products consist of noncondensable gases, namely CO_2, CO, H_2, N_2 and C_nH_m (among gaseous hydrocarbons the basic is CH_4), and condensable gases and vapor forming the liquid fraction under the normal conditions. Composition of each fraction and a quantitative ratio between them depend both on the final temperature of heating and on the heating rate. The yield of volatile products defines the mass loss of a raw material during its thermal processing. For measurements of the quantitative characteristics concerned with mass loss of raw materials during torrefaction and for determination of volatile content in raw material before and after thermal processing the thermogravimetric analysis (TGA) was carried out. For this purpose the thermogravimetric analyzer SDT Q600 was used. The SDT Q600 allowed also to make the differential scanning calorimetry (DSC) and was employed to investigate the influence of torrefaction conditions on the heating value of granulated biomass fuel.

RESULTS AND DISCUSSION

Torrefaction Process

The TGA curves, corresponding to the torrefaction of wood pellets at the different final temperatures, are shown in Fig. 1. There is also presented TGA curve, corresponding to the heating of wood pellets to 1000°C, which gives a general idea of the mass fraction of volatile products in the work material. Mass loss observed at the initial stage of heating (up to the temperature about 150°C) is caused by water extraction, i.e. drying of material, and characterizes its initial moisture content. In our case the moisture content of the samples was equal to 5.4% for wood pellets, 6.6% for peat pellets and 5.6% for straw pellets. Further mass loss is caused by a thermal decomposition of organic constituents of raw material.

Time history of the mass loss rate of wood pellets during torrefaction is well seen from the differential thermogravimetric (DTG) curves presented in Fig. 2:

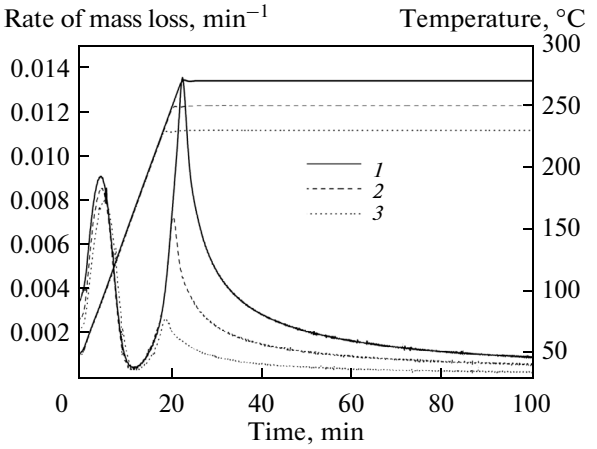

Fig. 2. Rates of mass loss and temperature profiles during the torrefaction of wood pellets at different torrefaction temperatures T_t: T_t = (1) 270, (2) 250, and (3) 230°C.

the first peak characterizes the drying rate of the sample, the second peak—the rate of thermal decomposition of the material. The maximum rate of mass loss is observed when the sample temperature reaches the value of T_t whereupon the rate decreases because of reduction of the sample mass. As appears from Fig. 2 in 100 minutes after the start of heating the rate of mass loss falls off practically on an order of magnitude. A similar behavior was observed for straw and peat pellets. Based on this fact during investigations of the influence of torrefaction on the thermotechnical characteristics of granulated biomass fuel the time of thermal processing was limited by the specified value.

As is known biomass consists of organic and mineral components. In turn organic part falls into hemicellulose, cellulose and lignin. Hemicellulose is the least thermostable organic component. According to [14, 15] thermal decomposition of hemicellulose accompanied with mass losses occurs in the temperature range of 180–320°C, cellulose—in the temperature range of 270–370°C. Thermal decomposition of lignin follows more uniformly in comparison with two other components, and is characterized by the temperature interval of 200–540°C.

DTG curves describing dynamics of mass loss during pyrolysis (heating up to 1000°C at the rate 10°C/min) of pieces from the original and torrefied wood, straw and peat pellets are presented in Fig. 3. In the DTG curves, corresponding to the original (untreated) wood and straw pellets, one can see three representative kinks (are marked by *1–3*) associated with thermal decomposition of hemicellulose *1*, cellulose *2* and lignin *3*. In the DTG curves, corresponding to the samples subjected to torrefaction, the kink concerned with thermal decomposition of hemicellulose decreases with increasing the torrefaction temperature and at T_t = 270°C disappears completely. It is evidence of practically complete absence of hemicellulose in

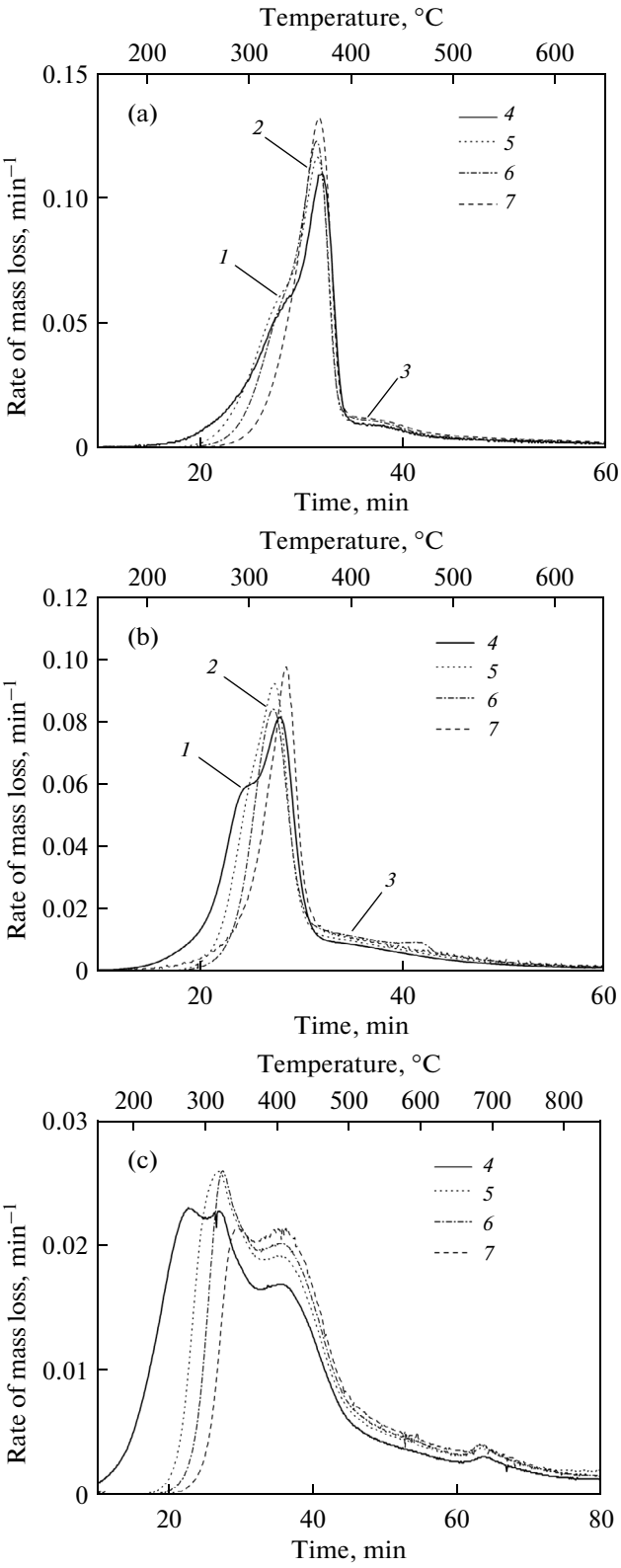

Fig. 3. Rate of mass loss during pyrolysis of untreated pellets and pellets torrefied at different torrefaction temperatures T_t: a—wood pellets, b—straw, c—peat. Heating rate is equal to 10°C/min: *4*—untreated, *5*—T_t = 230°C, *6*—250, *7*—270.

Table 1. Mass loss as a result of torrefaction, re-counted on dry basis (wt %)

Temperature of torrefaction, T_t, °C	Raw material		
	wood pellets	peat pellets	straw pellets
230	6.4	18	17
250	14	23	27
270	25	30	43

Table 2. Mass fraction of the volatile matter in the untreated and torrefied materials, re-counted on dry basis (wt %)

Temperature of torrefaction, T_t, °C	Raw material		
	wood pellets	peat pellets	straw pellets
230	81	60	66
250	79	57	62
270	76	53	51
Untreated raw material	82	64	72

the sample torrefied at this temperature. As peat is composed of partially decayed vegetable matter, which largely lost its cellular texture, the corresponding DTG curve has other representative kinks. From Fig. 3c one can see that the characteristic peculiarity of the peat DTG curve, located at a temperature below 300°C, disappears with increasing the torrefaction temperature that is evidence of decomposition of the least thermostable organic component of peat.

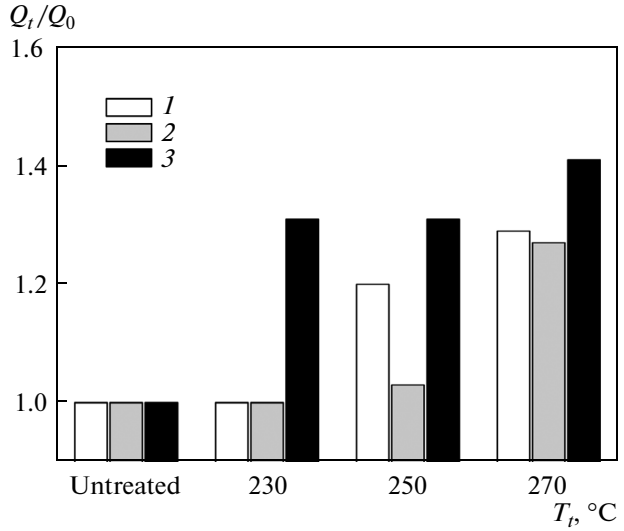

Fig. 4. Effect of torrefaction temperature T_t on heating value of pellets of different raw materials (Q_t and Q_0—heating value of torrefied and untreated pellets, re-counted on dry ash-free basis): *1*—straw pellets, *2*—wood, *3*—peat.

In Table 1 the data on mass loss for different types of initial raw materials as a result of torrefaction at different torrefaction temperatures T_t are submitted. From these data one can see that the smallest mass loss due to torrefaction is observed for wood pellets, the greatest—for straw pellets that is mainly related to the various content of hemicellulose in these raw materials [16]. Note, that the maximum mass losses as a result of pyrolysis of initial raw materials (heating up to the temperature of 1000°C) are equal to 82, 64, 72 wt % for pellets of wood, peat and straw, respectively.

Devolatilization and Heating Value

In consequence of torrefaction an initial raw material changes the thermotechnical properties, which are important, when it is used as a solid fuel. As a result of devolatilization the ratio between content of carbon, hydrogen and oxygen in a raw material is changed. Simultaneously there is changed the ratio between the content of volatile and solid matter. These changes have an essential influence on process of solid fuel burning. In particular, the combustion rate is generally defined by the combustion rate of a solid carbon residue. Solid carbon residue also makes the main contribution to the heating value of solid fuel. In Table 2 the data on content of volatile matter in the untreated raw materials and in the raw materials torrefied at different temperatures are presented. From the submitted data it follows that an increase of the torrefaction temperature T_t leads to a decrease of the content of volatile matter and, therefore, to an increase of mass fraction of solid carbon residue. In turn an increase of mass fraction of solid carbon residue leads to increase of heating value of fuel. The greatest difference between untreated and torrefied materials is observed for straw pellets.

It is necessary to note that a decrease of the volatile matter content leads to a decrease of soot content in combustion products of a solid fuel. Soot is formed as a result of thermal decomposition of hydrocarbon components contained in the volatile products and responsible for smoke emission. Thus decrease of the mass fraction of volatile components leads to improvement of consumer properties of solid fuel.

In Fig. 4 there are shown the data on influence of torrefaction temperature on the heating value of pellets of different biomass materials. From the presented data it follows that an increase of torrefaction temperature results in appreciable increase of heating value. The maximum growth is observed for peat pellets.

Hygroscopicity

Other important characteristic of a solid fuel is the limit moisture content W. Decomposition of organic part of a raw material, occurring during torrefaction,

causes a modification of its surface and internal structure, which is evidenced by electron micrographs. Along with the change in the chemical composition, accompanied by the destruction of the hydroxyl groups, this leads to loss of the hygroscopic properties of biomass [5].

In Fig. 5 there are shown the data on influence of the torrefaction temperature T_t on the limit moisture content W. The limit moisture content was measured as the ratio of the equilibrium mass of water retained by a material, situated in the air with 100% humidity at the temperature of 26°C, to the mass of dry material.

From the data presented in Fig. 5 one can see that the torrefaction allows essentially to improve the hydrophobic property of granulated fuel of the different biomass materials: the limit moisture content of pellets torrefied at $T_t = 270$°C is reduced practically twice in comparison with untreated pellets. The value of W for wood pellets is in a good agreement with the results of similar measurements presented in [11]. It is necessary to note, that untreated wood and straw pellets swelled and collapsed after holding during 24 hours in the air with 100% humidity at the temperature of 26°C. The torrefied pellets kept the form in the similar conditions.

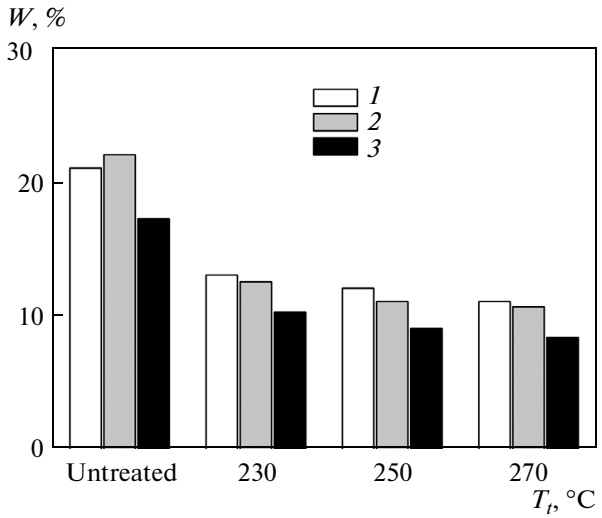

Fig. 5. Effect of torrefaction temperature T_t on limit moisture content W of pellets of different raw materials (for notations see Fig. 4).

CONVERSION OF VOLATILE TORREFACTION PRODUCTS INTO SYNTHESIS GAS

In torrefaction of a biomass the perceptible amount of volatile products is evolved (see Table 1). Usually the mass fraction of condensable volatiles is several times as much as noncondensable one. According to [17] the condensable fraction of volatile products consists mainly of acetic acid and water with modest quantities of methanol, formic acid, lactic acid, furfural and hydroxyl acetone. It is natural that the question of their utilization is very important from the ecological point of view. For this purpose the method of thermal conversion of gases and vapor escaping during pyrolysis of sawdust, proposed in [18], can be used. In [19, 20] the usage of the similar method as applied to pyrolitic conversion of various types of biomass into gaseous fuel was substantiated. In [21] it was applied also conformably to torrefaction.

In accordance with this method, the volatile products formed during heating of biomass raw material are passed through a porous carbon agent maintained at a fixed high temperature. The char residue obtained by pyrolysis, i.e. by heating in the inert gas environment up to the temperatures of 600–1000°C, of the same raw material can be used as such agent.

Owing to well-developed surface of char residue, a rapid heating of volatile products and intensive decomposition of the high-molecular organic components take place. In addition as a result of interaction of water vapor and carbon dioxide with a carbon surface a formation of hydrogen and carbon monoxide (the water gas reaction) and reduction of carbon dioxide to carbon monoxide (the Boudouard reaction) occur. As it was shown in [19, 20] at the temperature of the carbon agent about 1000°C and suitable time of interaction of volatile pyrolysis products with a carbon surface practically complete conversion of the last into synthesis gas, i.e. into a mixture of hydrogen and carbon monoxide, takes place.

Experiments were carried out on the setup described in [19] and consisted of a high-temperature two-chamber reactor. The volume yield and composition of gas at the reactor outlet were measured by eudiometric and chromatographic methods, respectively.

In Fig. 6 there are presented the data on the volume content of hydrogen and carbon monoxide in synthesis gas, which can be obtained as a result of high-temperature conversion of the volatile products forming during torrefaction of various biomass materials. Note that admixture of other gases, from which the basic is carbon dioxide, doesn't exceed 10% (by volume).

The heating value of the product synthesis gas is about of 11 MJ/m^3 that allows to consider it, as a quite acceptable gaseous fuel for power installations based on gas-piston engines. From this viewpoint, it is advisable to compare the energy consumption in the production of pellets with an energy which can be generated by the use of synthesis gas produced as a result of the thermal conversion of torrefaction volatile products. The volume yield of the synthesis gas, which can be produced by high-temperature processing of the volatile products formed as a result of torrefaction of 100 kg of pellets, is in the range from 20 to 55 m^3 depending on a type of raw material and the torrefaction temperature (see Fig. 6). Let average energy-conversion efficiency for electrogenerating installations on the basis of a gas-piston engine is equal to 30%. In this case the use of the synthesis gas, produced on tor-

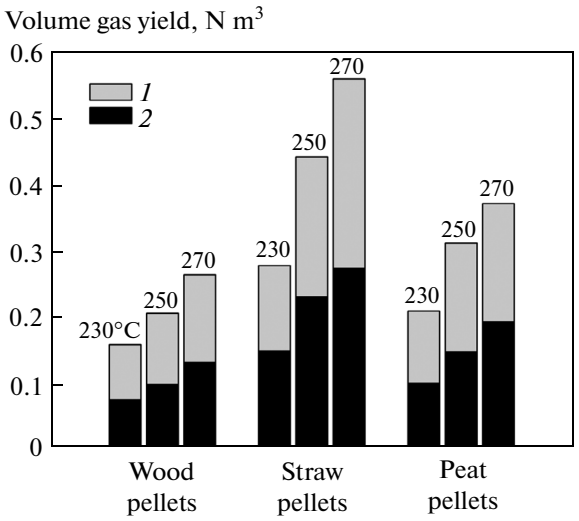

Fig. 6. Volume yield of hydrogen and carbon monoxide, produced by high-temperature processing of the volatile torrefaction products at different torrefaction temperatures T_t (marked above each bar) per one kg of initial raw material: *1*—CO, *2*—H_2.

refaction of 100 kg of pellets per hour, will permit to maintain an electrogenerating installation with power of 18–50 kW in operation. For comparison the electrical power of the plant for wood pellitization with productivity of 100 kg per hour doesn't exceed 7.5 kW and with a large supply can be provided at the expense of thermal conversion of torrefaction volatile products into synthesis gas.

CONCLUSIONS

As a result of performed experimental investigations it is shown that torrefaction of the granulated fuel from different biomass materials (wood, peat, straw) gives an opportunity to improve its consumer properties, namely, to reduce the limit moisture content practically in half and to increase the heating value noticeably. The volatile products obtained in the course of torrefaction can be converted into synthesis gas that allows to solve the problem of their utilization and simultaneously to increase the power efficiency of biomass processing. The considered approach can be used during engineering and creation of self-contained facilities operating directly in places of biomass production and intended for processing of different biomass materials (wood and agricultural waste, peat) into the granulated solid fuel with improved consumer properties.

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